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The China Space Station Telescope (CSST) is primarily designed for large-scale multi-color imaging and seamless spectroscopic survey, while also accommodating observations with an integral field spectrograph (IFS), multi-channel imaging, direct imaging of exoplanets, and terahertz-band observations. It is scheduled to be launched in about 2 yr. The telescope is equipped with a variety of terminal instruments. It has important scientific missions but limited observation time, so it is suggested to develop a 2.5 m coaxial telescope that will be co-orbiting with the space station. This additional telescope will mainly focus on time-domain surveys and IFS surveys. Its development budget is lower than the current 2 m off-axis telescope, CSST, but it offers superior system performance. Within the limited operational lifespan of the space station, it can significantly enhance the existing survey efficiency. Like the CSST, this telescope will be able to do multi-color imaging survey, and time-domain surveys are also under consideration.

Full Text

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2.5 m Space Station Co-orbiting Coaxial Telescope

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Abstract

The China Space Station Telescope (CSST) is primarily designed for large-scale multi-color imaging and seamless spectroscopic surveys, while also accommodating observations with an integral field spectrograph (IFS), multi-channel imaging, direct imaging of exoplanets, and terahertz-band observations. Scheduled for launch in approximately two years, the telescope will be equipped with a variety of terminal instruments. Despite its important scientific missions, observation time is limited. Therefore, we propose developing a 2.5 m coaxial telescope that will co-orbit with the space station, primarily focusing on time-domain surveys and IFS surveys. This additional telescope would have a lower development budget than the current 2 m off-axis CSST while offering superior system performance. Within the limited operational lifespan of the space station, it can significantly enhance survey efficiency. Like the CSST, this telescope will be capable of multi-color imaging surveys, and time-domain surveys are also under consideration.

Key words: space vehicles: instruments –telescopes –surveys

1. Introduction

Multi-color imaging and spectroscopic surveys are essential for studying the formation and evolution of celestial objects in the universe, yielding vast amounts of image and spectral data that drive new astronomical discoveries in the current era of big data.

The international astronomical community has made substantial progress in ground-based survey observations, including the 2dF Galaxy Redshift Survey in Australia (Lewis et al. 2002), the Sloan Digital Sky Survey (Gunn et al. 2006), the Dark Energy Spectroscopic Instrument in the United States (Doel et al. 2014), and the upcoming first light of the Rubin Observatory (Tyson & the LSST Collaboration 2002). These large-scale projects have achieved or are expected to achieve remarkable scientific results in studying the large-scale structure of the universe, galaxy physics, quasars, and related fields.

In 2009, China built the LAMOST (Guo Shoujing Telescope) facility, which pioneered large-scale spectroscopic surveys with simultaneous observations of thousands of celestial objects (Cui et al. 2012). As of December 2024, LAMOST has released more than 33 million spectra to domestic and international partners , establishing China as an international hub for seamless spectroscopic surveys and helping Chinese astronomy maintain a leading position in Milky Way and stellar research.

Space-based astronomy has been revolutionized by the Hubble Space Telescope (HST), whose high-resolution imaging capabilities have advanced studies of supernova remnants, galaxy formation, and other cosmic phenomena (Ferguson et al. 2000). Its successor, the James Webb Space Telescope (JWST), launched on December 25, 2021, features a 6.5 m aperture, a wavelength range of 0.6–28.5 m, and a field of view (FOV) of approximately 0.046 square degrees (Gardner et al. 2006). On July 1, 2023, ESA' s Euclid space telescope launched with a smaller 1.2 m aperture but a much larger 0.5 square degree FOV—about 186 times that of JWST (Euclid Collaboration 2004). This wide-field design enables Euclid to survey larger sky areas more efficiently.

Euclid' s primary scientific goal is to study dark matter and dark energy and map the large-scale structure of the universe through wide-field surveys.

NASA's Nancy Grace Roman Space Telescope, scheduled for launch in 2027, features a 2.4 m aperture identical to HST' s but with an FOV 100 times larger. Its 300-megapixel wide-field instrument can survey larger sky areas per observation, enabling efficient large-scale surveys (Akeson et al. 2019). Roman' s primary scientific objective is to study dark energy by observing the large-scale structure of the universe—galaxy distribution and shapes—and cosmic expansion history to understand dark energy' s nature and evolution. Its wide-field instrument will measure light from billions of galaxies to precisely characterize dark energy' s effects on cosmic expansion. Additionally, Roman will conduct a microlensing survey expected to discover approximately 2,600 exoplanets.

The China Space Station Telescope (CSST) is a large space-based astronomical telescope planned as part of China' s manned spaceflight project (Zhan 2011). With a 2 m aperture and a one square degree FOV, CSST can image approximately 50,000 galaxies and obtain spectra for over 2,000 galaxies per observation, enabling efficient large-scale surveys. The telescope is equipped with multiple instruments: a survey module, multi-channel integral field spectrograph (IFS), exoplanet imaging coronagraph, and high-sensitivity terahertz module. However, only 60% of observation time is allocated to surveys.

As early as October 5, 2013, Su Dingqiang proposed a co-orbiting 2 m telescope scheme via email to relevant leaders and researchers. The concept uses Tiangong space station as a space port: the telescope normally flies independently in the same orbit, 5–10 km or more from the station, but can actively rendezvous and dock for resupply, repair, or upgrades, ensuring normal operation and extending service life. This co-orbiting scheme allows the space station to operate multiple telescopes, greatly improving scientific capability and operational efficiency. In 2014, Su Dingqiang and Cui Xiangqun published the coaxial 2 m space telescope scheme in RAA (Su & Cui 2014). The first scheme locates the telescope inside the space station cabin with these characteristics: (1) a coudé system with relay mirror (SYZ relay mirror); (2) a yoke frame vibration-isolated from the station to eliminate high-frequency vibration; (3) two-level coarse and fine control for pointing and tracking; (4) rear-end instruments arranged around a switching mirror with one-dimensional module rotation for instrument selection; (5) two axes where Axis I and Axis II correspond to the polar and declination axes of ground-based equatorial telescopes, with Axis I pointing to the space station orbit pole, allowing rotation around both axes for tracking and pointing. The second scheme is the co-orbiting version with essentially the same optical system but slightly different structural layout due to space station envelope constraints.

Although the current 2 m off-axis CSST is primarily designed for multi-color photometric surveys, it must also accommodate integral field units (IFUs), spectroscopy, exoplanet imaging, and terahertz observations. Given these important scientific tasks and limited observation time, we propose developing an additional 2.5 m coaxial optical telescope that co-orbits with the space station. During the station' s limited lifespan, this additional telescope would enable more efficient and extensive scientific observations.

2. Coaxial and Off-axis Optical Systems

In a coaxial optical system, the center of each optical element' s aperture coincides with the optical axis, resulting in central obscuration. In an off-axis system, light rays and the optical elements' central axes are not collinear, eliminating central obscuration.

The development of coaxial and off-axis telescopes began in the same era. In 1616, Zucchi designed the Herschel-type forward-looking reflector telescope (see Figure 1 [Figure 1: see original paper]), considered the first off-axis telescope. The first Cassegrain-type telescope with tilted components was the Brachy telescope by Forster and Fritsch in 1876. In 1953, Kurt published a systematic study of off-axis telescopes using two tilted mirrors, called "Schiefspiegler" telescopes. Coaxial telescopes developed following the invention of the single-mirror Newtonian telescope (see Figure 1 [Figure 1: see original paper]), with subsequent development of the two-mirror Cassegrain and Ritchey–Chrétien systems. Karl Schwarzschild first proposed the three-mirror reflective optical system concept in 1905, leading to various three-mirror coaxial and off-axis configurations (three-mirror anastigmat systems). The history of telescope development is detailed in *Reflecting Telescope Optics I* (Wilson 1996).

Astronomical optical telescopes predominantly adopt coaxial optical systems. Throughout the 400-year history of astronomical telescopes, classical coaxial systems have remained dominant, even as optical and mechanical manufacturing, computer, electronic, and thermal control technologies have advanced rapidly in recent decades.

Internationally, more than ten 8–10 m class optical telescopes have been built, including the 10 m Keck (Nelson & Mast 1986), 8.1 m Gemini (Mountain et al. 1994), and 8.2 m VLT (ESO 1998), all using coaxial systems. Future 30 m class telescopes such as the Thirty Meter Telescope (Sanders 2013), Extremely Large Telescope (Delabre 2008), and Giant Magellan Telescope (McCarthy et al. 2016) will also adopt coaxial systems.

Space-based telescopes such as the 2.4 m HST (Ferguson et al. 2000) and 3.5 m Herschel infrared telescope (Sein et al. 2003) also use coaxial systems. Recently launched or upcoming space optical telescopes—including 1.2 m Euclid (Euclid Collaboration 2004), 6.5 m JWST (Gardner et al. 2006), and 2.4 m Roman (Akeson et al. 2019)—have adopted coaxial or nearly coaxial designs. To date, only a few solar telescopes use off-axis systems, such as the 4 m Daniel K. Inouye Solar Telescope (DKIST; Rimmele et al. 2020) and the 1.7 m telescope at Big Bear Solar Observatory . In terms of image quality, for optical systems with identical aperture, focal ratio, and FOV, coaxial systems deliver superior performance compared to off-axis systems.

Astronomical observations require area FOV coverage with image quality near the diffraction limit across the entire field. Coaxial systems offer advantages in spot diagram symmetry, simple point-spread function (PSF) shapes, and gentle variations across the FOV, which is particularly beneficial for detecting cosmic dark matter through weak gravitational lensing (WL). In WL-focused telescope projects, scientific requirements documents explicitly specify PSF ellipticity requirements, as seen in Euclid and JWST (Euclid Collaboration 2004; Gardner et al. 2006).

In terms of optical fabrication and testing cost and risk, off-axis primary mirrors have approximately 2–3 times the asphericity of coaxial mirrors. For off-axis systems with focal ratios near 1, fabrication and testing difficulties increase substantially, making development costs and risks significantly higher than equivalent coaxial systems, even when manufacturable. For example, polishing DKIST' s 4 m off-axis primary mirror cost approximately $11 million, whereas a 4 m coaxial primary mirror would cost about $4 million . We believe large-aperture space telescopes in the 4–8 m range should also employ coaxial optical systems.

3. 2.5 m Coaxial Telescope with Space Station Co-orbiting

The proposed 2.5 m space station co-orbiting coaxial telescope uses the same optical system as the 2 m coaxial design (optical layouts shown in Figure 2 [Figure 2: see original paper]), originally designed by Genrong Liu in 2010, but with aperture increased to 2.5 m or larger depending on launch constraints. The focal ratio is approximately F/14 with a 1.5° FOV diameter. This system derives from the Chinese 2.16 m telescope' s coudé system (initially proposed in June 1972 and published in Su et al. 1990).

The optical system delivers geometric imaging quality better than the diffraction limit across the FOV, with 80% enclosed energy spot diameters smaller than 0.1 arcsecond; the energy profile is shown in Figure 3 [Figure 3: see original paper].

Table 1 compares the basic optical performance of the 2 m unobscured off-axis system and the 2.5 m coaxial obscured system, demonstrating that the 2.5 m coaxial system provides superior light-collecting area and image quality.

The Modulation Transfer Functions (MTF) for different configurations are plotted in Figure 4 [Figure 4: see original paper]. While the 2 m unobscured system shows slightly better MTF at medium and low frequencies, the 2.5 and 2.7 m obscured systems significantly outperform it at high frequencies, which are most important for astronomical observations.

Étendue, the product of a telescope' s light-gathering area (in m^2) and FOV (in deg^2), is a widely used parameter describing survey efficiency. Higher angular resolution enables greater survey efficiency. The sky survey rate is defined as étendue divided by the square of the angular image size.

Ground-based telescopes achieve approximately 1 arcsecond imaging quality due to atmospheric turbulence (as good as 0.7 arcseconds at excellent sites), whereas a 2.5 m space telescope can reach about 0.1 arcsecond quality. Consequently, despite its smaller aperture and FOV, the 2.5 m telescope' s sky survey rate can be comparable to a 6.5 m ground-based telescope with a 3.5° FOV. This 2.5 m telescope will focus primarily on time-domain and IFS surveys, with extremely low-dispersion spectroscopic surveys also under consideration.

4. Conclusion

(1) This Letter proposes a 2.5 m coaxial telescope co-orbiting with the space station, featuring a 1.76 square degree FOV for time-domain and IFS surveys (with extremely low-dispersion spectroscopic surveys also considered); after the space station ceases operations, the telescope can continue independent survey observations.

(2) Compared to off-axis systems, coaxial systems achieve higher precision at lower cost. Under identical budget and launch constraints, a 2.5 m space coaxial telescope costs less (approximately one-third to one-half the budget) with a shorter development cycle.

(3) The 2.5 m coaxial telescope offers superior aperture and optical performance: 1.35 times greater light-collecting area and 1.16 times better diffraction resolution compared to the 2 m off-axis system.

(4) The coaxial secondary mirror and spider structure do not produce cross-vane diffraction effects on faint sources; any impact on bright sources is uniform and can be removed algorithmically, as demonstrated by HST and JWST observations.

(5) We recommend expeditious development of this additional 2.5 m coaxial telescope, positioned at an appropriate distance from the existing 2 m CSST.

(6) This additional 2.5 m coaxial telescope would considerably enhance sky survey efficiency with minimal additional cost during the station' s operational lifetime.

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